parameters in Table K-9 describe the radionuclide exposure to the gardener where applicable (for example, exposure parameters related to the fish are not applicable to the gardener).

K.2.4.2 Direct Exposure

The analysis evaluated potential external radiation dose rates to the maximally exposed individual for a commercial independent spent fuel storage installation because this type of facility would provide the highest external exposures of all the facilities analyzed in this appendix. Maximum dose rates over the 10,000-year analysis period were evaluated for each region. The maximally exposed individual was assumed to be 10 meters (about 33 feet) from an array of concrete storage modules containing 1,000 MTHM of commercial spent nuclear fuel. The maximum dose rate varied between regions depending on how long the concrete shielding would remain intact (Table K-1).

The direct gamma radiation levels were calculated (DIRS 101556-Davis 1998, all). To ensure consistency between this analysis and the TSPA-VA, the same radionuclides were used for the design of the Yucca Mountain Repository surface facility shielding (DIRS 104603-CRWMS M&O 1995, Attachment 9.5). Radionuclide decay and radioactive decay product ingrowth over the 10,000-year analysis period were calculated using the ORIGEN computer program (DIRS 147923-RSIC 1991, all).

Neutron emissions were not included because worst-case impacts (death within a short period of exposure) would be the same with or without the neutron component.

K.2.5 ACCIDENT METHODOLOGY

Spent nuclear fuel and high-level radioactive waste stored in above-ground dry storage facilities would be protected initially by the robust surrounding structure (either metal or concrete) and by a steel storage container that contained the material. Normal storage facility operations would be primarily passive because the facilities would be designed for cooling via natural convection. DOE evaluated potential accident and criticality impacts for both Scenario 1 (institutional control for 10,000 years) and Scenario 2 (assumption of no effective institutional control after approximately 100 years with deterioration of the engineered barriers initially protecting the spent nuclear fuel or high-level radioactive waste).

For Scenario 1, human activities at each facility would include surveillance, inspection, maintenance, and equipment replacement when required. The facilities and the associated systems, which would be licensed by the Nuclear Regulatory Commission, would have certain required features. License requirements would include isolation of the stored material from the environment and its protection from severe accident conditions (10 CFR 50.34). The Nuclear Regulatory Commission requires an extensive safety analysis that considers the impacts of plausible accident-initiating events such as earthquakes, fires, high winds, and tornadoes. No plausible accident scenarios have been identified that result in the release of radioactive material from the storage facilities (DIRS 103449-PGE 1996, all; DIRS 103177-CP&L 1989, all). In addition, the license would specify that facility design requirements include features to provide protection from the impacts of severe natural events. These requirements and analyses must demonstrate that the facilities can withstand the most severe wind loading (tornado winds and tornado-generated missiles) and flooding from the Probable Maximum Hurricane with minimal release of radioactive material. This analysis assumed maintenance of these features indefinitely for the storage facilities.

DOE performed a scoping analysis to identify the kinds of events that could lead to releases of radioactive material to the environment prior to degradation of concrete storage modules and found none. The two events determined to be the most challenging to the integrity of the concrete storage modules would be the crash of an aircraft into the storage facility and a severe seismic event.

- DIRS 103711-Davis, Strenge, and Mishima (1998, all) evaluated the postulated aircraft crash and subsequent fire at a storage facility. The analysis showed that falling aircraft components produced by such an event would not penetrate the storage facility and that a subsequent fire would not result in a release of radioactive materials.

- For the seismic event, meaningful damage would be unlikely because storage facilities would be designed to withstand severe earthquakes. Even if such an event caused damage, no immediate release would occur because no mechanism has been identified that would cause meaningful fuel pellet damage to create respirable airborne particles. If this damage did not occur, the source term would be limited to gaseous fission products, carbon-14, and a very small amount of preexisting fuel pellet dust. Subsequent repairs to damaged facilities or concrete storage modules would preclude the long-term release of radionuclides.

Criticality events are not plausible for Scenario 1 because water, which is required for criticality, could not enter the dry storage canister. The water would have to penetrate several independent barriers, all of which would be maintained and replaced as necessary under Scenario 1.

Under Scenario 2, facilities would degrade over time and the structures would gradually deteriorate and lose their integrity. The analysis determined that two events, an aircraft crash and inadvertent criticality, would be likely to dominate the impacts from accidents, as described in the following paragraphs.

K.2.5.1 Aircraft Crash

DOE determined that an aircraft crash into a degraded concrete storage module would be a severe accident-initiating event that could occur at the storage sites. This event would provide the potential for the airborne dispersion of radioactive material to the environment and, as a result, the potential for exposure of individuals who lived in the vicinity of the site. The aircraft crash could result in mechanical damage to the storage casks and the fuel assemblies they contained, and a fire could result. The fire would provide an additional mechanism for dispersion of the radioactive material. The frequency and consequences of this event are described in detail in DIRS 103711-Davis, Strenge, and Mishima (1998, all).

The aircraft assumed for the analysis is a midsize twin-engine commercial jet (DIRS 103711-Davis, Strenge, and Mishima 1998, p. 2). The area affected by a crash was computed using the DOE standard formula (DIRS 101810-DOE 1996, Chapter 6) in which the aircraft could crash directly into the side or top of the concrete storage modules, or could strike the ground in the immediate vicinity of the facility and skid into the concrete storage modules. Using this formula, the dimensions of a typical storage facility as shown in Chapter 2, Figure 2-33, and the aircraft configuration would result in an estimated aircraft crash frequency of 0.0000032 (3 in 1 million) crashes per year (DIRS 103711-Davis, Strenge, and Mishima 1998, p. 5). This frequency is within the range that DOE typically considers the design basis, which is defined by DOE as 0.000001 or greater per year (DIRS 104601-DOE 1993, p. 28).

The analysis estimated the consequences of the aircraft crash on degraded concrete storage modules. The twin-engine jet was assumed to crash into an independent spent fuel storage installation that contained 100 concrete storage modules, each containing 24 pressurized-water reactor fuel assemblies. Using the penetration methodology from DIRS 101810-DOE (1996, Chapter 6), an aircraft crash onto these concrete storage modules could penetrate 0.8 meter (2.6 feet). Because the concrete storage modules have thicker walls, the crash projectiles would not penetrate the reinforced concrete in the as-constructed form. Thus, DOE determined that the aircraft crash would not cause meaningful consequences until the concrete storage modules were considerably degraded, when an aircraft projectile could penetrate a concrete storage module and damage a storage cask (DIRS 103711-Davis, Strenge, and Mishima 1998, p. 7). The degradation process is highly location-dependent, as noted in Section K.2.1.1. For sites in northern climates, the degradation would be relatively rapid due to the freeze/thaw cycling that would expedite concrete breakup; considerable degradation could occur in 200 to 300 years. For southern climates, the degradation would be much slower. Thus, an aircraft crash probably would not result in meaningful consequences for a few hundred to a few thousand years, depending on location. The timing is of some importance because the radioactive materials in the fuel would decay over time, and the potential for radiation exposure would decline with the decay.

The analysis assumed that the aircraft crash occurred 1,000 years after the termination of institutional control at a facility where the concrete had degraded sufficiently to allow breach of the dry storage canister. Computing public impacts from the air crash event requires estimating the population to a distance of 80 kilometers (50 miles) from a hypothetical site (the distance beyond which impacts from an airborne release would be very small). This analysis considered two such sites, one in an area of a high population site and one in an area of low population. The average population around all of the sites in each of the five regions defined in Figure K-2 was computed based on 1990 census data. The average ranged from a high of 330 persons per square mile in region 1 (high population) to a low of 77 persons per square mile in region 4 (low population). Both of these population densities (assumed to be uniform around the hypothetical sites) were used in the consequence calculation.

Estimating the amount of airborne respirable particles that would result from a crash requires assumptions about the impact and resulting fire. The impact of the jet engines probably would cause extensive damage to the fuel assemblies in the degraded concrete storage module. The fuel tanks in the aircraft would rupture, and fuel would disperse around the site, collect in pools, and ignite into a fire. The estimated fraction of the fuel converted to respirable airborne dust would be 0.12 percent (DIRS 103711-Davis, Strenge, and Mishima 1998, p. 9). The fire would cause a thermal updraft that could loft the fuel pellet dust into the atmosphere.

The consequences from the event were computed with the MACCS2 program (DIRS 101897-Jow et al. 1990, all). This model has been used extensively by the Nuclear Regulatory Commission and DOE to estimate impacts from accident scenarios involving releases of radioactive materials. The model computes dose to the public from the direct radiation by the cloud of radioactive particles released during the accident, from inhaling particles, and from consuming food produced from crops and grazing land that could be contaminated as the particles are deposited on the ground from the passing cloud. The food production and consumption rates are based on generic U.S. values (DIRS 103776-Kennedy and Strenge 1992, pp 6.19 to 6.28; DIRS 103168-Chanin and Young 1998, all). The program computes the dispersion of the particles as the cloud moves downwind. The dispersion would depend on the weather conditions (primarily wind speed, stability, and direction) that existed at the time of the accident. This calculation assumed median weather conditions and used annual weather data from airports near the centers of the regions.

K.2.5.2 Criticality

DOE evaluated the potential for nuclear criticality accidents involving stored spent nuclear fuel. A criticality accident is not possible in high-level radioactive waste because most of the fissionable atoms were removed or the density of fissionable atoms was reduced by the addition of glass matrix. Nuclear criticality is the generation of energy by the fissioning (splitting) of atoms as a result of collisions with neutrons. The energy release rate from the criticality event can be very low or very high, depending on several factors, including the concentration of fissionable atoms, the availability of moderating materials to slow the neutrons to a speed that enables them to collide with the fissionable atoms, and the presence of materials that can absorb neutrons, thus reducing the number of fission events.

Criticality events are of concern because under some conditions they could result in an abrupt release of radioactive material to the environment. If the event were energetic enough, the dry storage canister could split open, fuel cladding failure could occur, and fragmentation of the uranium dioxide fuel pellets could occur.

The designs of existing dry storage systems for spent nuclear fuel, in accordance with Nuclear Regulatory Commission regulations (10 CFR Part 72) preclude criticality events by various measures, including primarily the prevention of water entering the dry storage canister. If water is excluded, a criticality cannot occur.

If institutional control was maintained at the dry storage facilities (Scenario 1), a criticality is not plausible because the casks would be monitored and maintained such that introduction of water into the canister would not be possible. However, under Scenario 2, eventual degradation (corrosion) of the dry storage canisters could lead to the entry of water from precipitation, at which point criticality could be possible if other conditions were met simultaneously.

The analysis considered three separate criticality events:

- A low-energy event that involved a criticality lasting over an intermediate period (minutes or more). This event would not produce high temperatures or generate large additional quantities of radionuclides. Thus, no fuel cladding failures and no meaningful increase in consequences would be likely.

- An event in which a system went critical but at a slow enough rate so the energy release would not be large enough to produce steam, which would terminate the event. This event could continue over a relatively long period (minutes to hours), and would differ from the low-energy event in that the total number of fissions could be very large, and a large increase in radionuclide inventory could result. This increase could double the fission product content of the spent nuclear fuel. No fuel cladding failures would be likely in this event, so no abrupt release of radionuclides would occur.

- An energetic event in which a system went critical and produced considerable fission energy. This event could occur if seriously degraded fuel elements collapsed abruptly to the bottom of the canister in the presence of water that had penetrated the canister. This event would produce high fuel temperatures that could lead to cladding rupture and fuel pellet oxidation. The radiotoxicity of the radionuclide inventory produced by the fission process would be comparable to the inventory in the fuel before the event.

The probability of a criticality occurring as described in these scenarios is highly uncertain. However, DOE expects the probability would be higher for the first two events, and much lower for the third (energetic energy release). Several conditions would have to be met for any of the three events to occur. The concrete storage module and dry storage canister must have degraded such that water could enter but not drain out. The fuel would have to contain sufficient fissionable atoms (uranium-235, plutonium 239) to allow criticality. This would depend on initial enrichment (initial concentration of uranium-235) and burnup of the fuel in the reactor before storage (which would reduce the uranium-235 concentration). Because a small amount of spent nuclear fuel would be likely to have appropriate enrichment burnup combinations that could enable criticality to occur, none of the criticality events can be completely ruled out. The energetic criticality event is the only one with the potential to produce large impacts. Such an event would be possible, but would be highly unlikely; its consequences would be uncertain. The event could cause a prompt release of radionuclides. However, the amount released would not be likely to exceed that released by the aircraft crash event evaluated above. Thus, this analysis did not evaluate specific consequences of a criticality event.

K.3 Results

K.3.1 RADIOLOGICAL IMPACTS

Impacts to human health from long-term environmental releases and human intrusion were estimated using the methods described in Section K.2 and in supporting technical documents (DIRS 101925-Sinkowski 1998, all; DIRS 101852-Jenkins 1998, all; DIRS 104597-Battelle 1998, all; DIRS 101910, 101911-Poe 1998, all; DIRS 101912-Poe and Wise 1998, all; DIRS 101935-Toblin 1999, all; DIRS 101936-Toblin 1999, all; DIRS 101937-Toblin 1998, all). The radiological impacts on human health would include internal exposures due to the intake of radioactive materials released to surface water and groundwater.

Six of the seven radionuclides listed in Table K-4 would contribute more than 99 percent of the total dose. Table K-11 lists the estimated radiological impacts by region during the last 9,900 years under Scenario 2 for the Proposed Action and Module 1 inventories of spent nuclear fuel and high-level radioactive waste. As noted above, these impacts would be to the public from drinking water from the major waterways contaminated by surface-water runoff of radioactive materials from degraded spent nuclear fuel and high-level radioactive waste storage facilities (DIRS 101935-Toblin 1999, all; DIRS 101936-Toblin 1999, all). Figure K-7 shows the locations of all commercial nuclear and DOE waste storage sites in the United States and more than 20 potentially affected major waterways. At present, 30.5 million people are served by municipal water systems with intakes along the potentially affected portions of these waterways. Over the 9,900-year analysis period, about 140 generations would be potentially affected. However, because releases are not estimated to occur during about the first 1,000 years for most regions, the potential affected population could be as high as 3.9 billion.

SCENARIO 2 IMPACTS

The principal long-term human health consequences from the storage of spent nuclear fuel and high-level radioactive waste would result from rainwater flowing through degraded storage facilities where it would dissolve the material. The dissolved material would travel through groundwater and surface-water runoff to rivers and streams where people could use it for domestic purposes such as drinking water and crop irrigation. The Scenario 2 analysis estimated population impacts resulting only from the consumption of contaminated drinking water and exposures resulting from land contamination due to periodic flooding, although other pathways, such as eating contaminated fish, could contribute additional impacts larger than those from drinking water for selected individuals in the exposed population.

Table K-11 indicates the variability of collective doses and potential impacts in the five regions analyzed (see Section K.2.1.6). The variability among regions is due to differences in types and quantities of spent nuclear fuel and high-level radioactive waste, annual precipitation, size of affected populations, and surface-water bodies available to transport the radioactive material.

Table K-11 also indicates that the Proposed Action inventory would produce a collective drinking water dose of 6.6 million person-rem over 9,900 years, which could result in an additional 3,300 latent cancer fatalities in the total potentially exposed population of 3.9 billion, in which about 900 million fatal cancers [using the lifetime fatal cancer risk of 24 percent (DIRS 101849-NCHS 1993, p. 5)] would be likely to occur from all other causes. Figures K-8 and K-9 show the Proposed Action inventory regional collective doses and potential latent cancer fatalities, respectively, for approximately 140 consecutive 70-year lifetimes that would occur during the 9,900-year analysis period. The peaks shown in Figures K-8 and K-9 would result from the combination of the sites that drain to the Mississippi River and the relatively large populations potentially affected along these waterways. These values include

Table K-11. Estimated collective radiological impacts to the public from continued storage of Proposed Action and Module 1 inventories of spent nuclear fuel and high-level radioactive waste at commercial and DOE storage facilities – Scenario 2.[a]

	9,900-year population dose[b] (person-rem)		9,900-year LCFs		Years until peak impact[c]	
Region	Proposed Action	Module 1	Proposed Action	Module 1	Proposed Action	Module 1
1	1,800,000	1,820,000	900	900	1,400	1,400
2	760,000	1,260,000	380	630	5,100	8,300
3	3,500,000	3,650,000	1,800	1,830	3,400[d]	3,400[d]
4	70,000	138,000	30	69	3,900	3,900
5	460,000	461,000	230	230	7,100	7,000
Totals	***6,590,000***	***7,330,000***	***3,340***	***3,700***		

a. Total population (collective) dose from drinking water pathway over 9,900 years.

b. LCF = latent cancer fatality; additional number of latent cancer fatalities for the exposed population group based on an assumed risk of 0.0005 latent cancer fatality per person-rem of collective dose (DIRS 101857-NCRP 1993, p. 112).

c. Years after 2116 when the maximum doses would occur.

d. Year of combined U.S. peak impact would be the same as for Region 3 peak impact, because the predominant impact would be in Region 3.

impacts for the Proposed Action inventory only. Similar curves for the Module 1 inventory are not shown because of their similarity to those for the Proposed Action inventory. As listed in Table K-11, the impacts from the Module 1 inventory would be approximately 20 percent greater than for the Proposed Action inventory.

The additional 3,300 Proposed Action latent cancer fatalities (or 3,700 Module 1 latent cancer fatalities) over the 10,000-year analysis period would not be the only negative impact. Under Scenario 2, more than 20 major waterways of the United States (for example, the Great Lakes, the Mississippi, Ohio, and Columbia rivers, and many smaller rivers along the Eastern Seaboard) that currently supply domestic water to 30.5 million people would be contaminated with radioactive material. The shorelines of these waterways would be contaminated with long-lived radioactive materials (plutonium, uranium, americium, etc.) that would result in exposures to individuals who came into contact with the sediments, potentially increasing the number of latent cancer fatalities. Each of the 72 commercial and 5 DOE sites throughout the United States would have potentially hundreds of acres of land and underlying groundwater systems contaminated with radioactive materials at concentrations that would be potentially lethal to anyone who settled near the degraded storage facilities. The radioactive materials at the degraded facilities and in the floodplains and sediments would persist for hundreds of thousands of years.

As mentioned above, DOE only estimated potential collective impacts resulting from the consumption of contaminated surface water. However, other pathways (food consumption, contaminated floodplains, etc.) that could contribute to collective dose were evaluated (DIRS 101936-Toblin 1999, all; DIRS 150990-Rollins 1998, all) to determine their relative importance to the drinking water pathway. These pathways included the following:

- Consumption of vegetables irrigated with contaminated water
- Consumption of meat and milk from animals that drank contaminated water or were fed with contaminated feed
- Consumption of contaminated finfish and shellfish
- Direct exposure to contaminated shoreline sediments
- Exposures resulting from contamination of floodplains during periods of high stream (river) flow

These analyses determined that an individual living in a contaminated floodplain and consuming vegetables irrigated with contaminated surface water could receive a radiation exposure dose three times

Legend

★ Commercial sites

Note: The EIS analysis considered three commercial site pairs — Salem and Hope Creek, Nine Mile Point and FitzPatrick, and Dresden and Morris — to be single sites due to their proximity to each other.

◉ DOE sites

Note: The EIS analysis included the high-level radioactive waste at West Valley. The State of New York owns the high-level radioactive waste and the site. Under the West Valley Demonstration Project Act, DOE is responsible for solidifying and transporting the high-level radioactive waste to a repository.

Note: The Great Lakes and the St. Lawrence Seaway are considered major waterways.

Source: Modified from DIRS 101911-Poe (1998, p. 13).

Figure K-7. Major waterways near commercial and DOE sites.

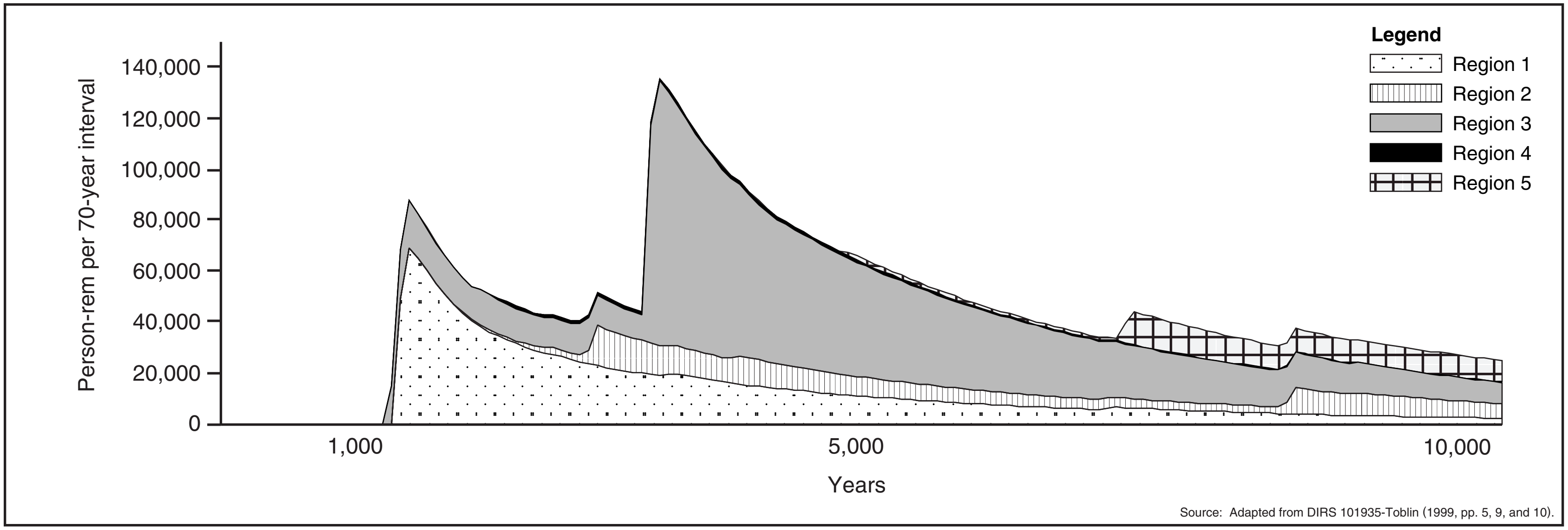

Figure K-8. Regional collective dose from the Proposed Action inventory under No-Action Scenario 2.

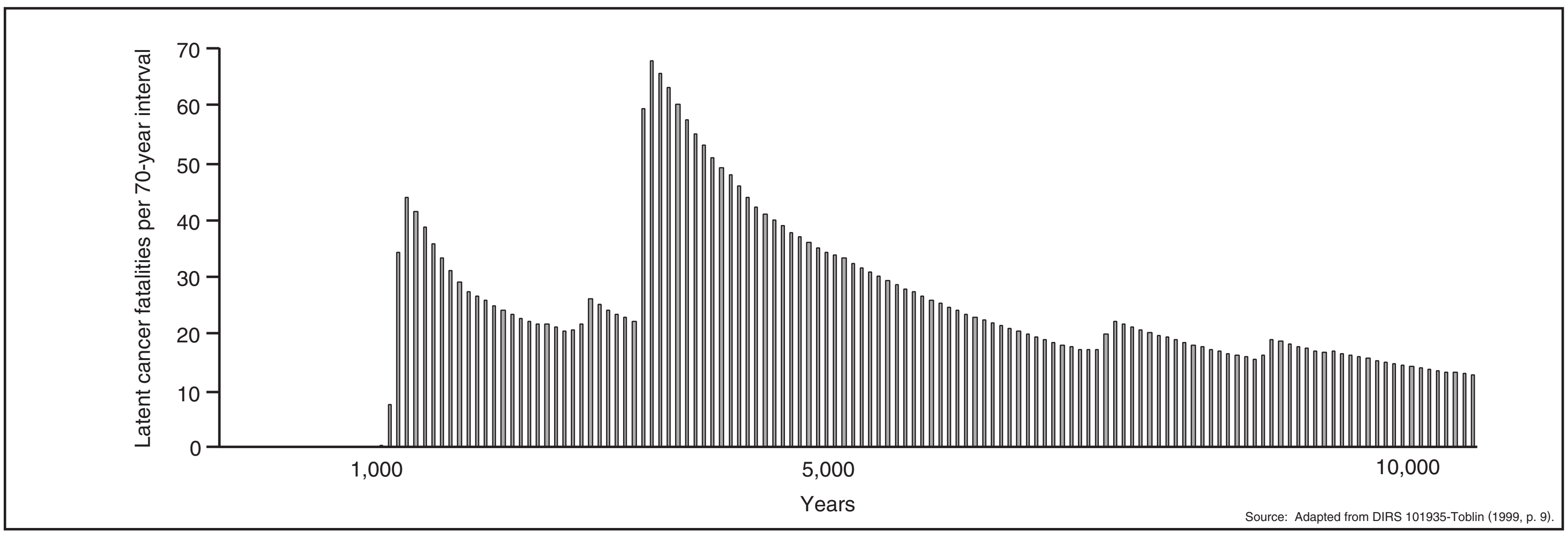

Figure K-9. Total potential latent cancer fatalities throughout the United States from the Proposed Action inventory under No-Action Scenario 2.

higher than that from the consumption of contaminated surface water only (DIRS 101936-Toblin 1999, p. 3). In addition, the analysis determined that impacts to 30 million individuals potentially living in contaminated floodplains would be less than 10 percent of the collective impacts shown in Figure K-9 and, therefore, did not include them in the estimates because DOE did not want to overestimate the impacts from Scenario 2.

DOE evaluated airborne pathways (DIRS 147905-Mishima 1998, all) and judged that potential impacts from those pathways would be very small in comparison to impacts from liquid pathways because the degraded facility structures would protect the radioactive material from winds. To simplify the analysis, impacts to the public from radiation emanating from the degraded storage facilities were not included. Those impacts were judged to represent a small fraction of the impacts calculated for the liquid pathways (Table K-11).

Estimates of localized impacts (DIRS 101937-Toblin 1998, p. 1) assumed that individuals (onsite and near-site gardeners) would take up residence near the degraded storage facilities and would consume vegetables from their gardens irrigated with groundwater withdrawn from the contaminated aquifer directly below their locations. In addition, the onsite gardener would be exposed to external radiation emanating from the exposed dry storage canisters; therefore, the onsite gardener would be the maximally exposed individual.

Table K-12 lists the internal estimated dose rates (see Section K.2.4.1 for details) and the times for peak exposure for each of the five regions.

Table K-12. Estimated internal dose rates (rem per year) and year of peak exposure[a] (in parentheses) for the onsite and near-site gardeners – Scenario 2.[b]

	Maximally exposed individual distances (meters)[c] from storage facilities			
Region	10[d]	150	1,000	5,000
1	3,100 (1,800)	670 (2,200)	51 (2,000)	12 (2,600)
2	100 (2,700)	96 (2,000)	12 (2,900)	2 (7,100)
3	3,100 (1,800)	1,800 (2,000)	150 (2,600)	31 (6,000)
4	140 (3,200)	130 (3,900)	14 (4,800)	2 (9,300)
5	3,300 (4,600)	180 (5,300)	59 (5,300)	2 (6,100)

a. Years after facility maintenance ended.
b. Source: Adapted from DIRS 101937-Toblin (1998, Table 4, p. 5).
c. To convert meters to feet, multiply by 3.2808.
d. The maximally exposed individual would be the onsite gardener.

The regional dose rates listed in Table K-12 would depend on the concentration of contaminants (primarily plutonium) in the underlying aquifer from which water was extracted and used by the gardener for consumption and crop irrigation. These aquifer concentrations, in turn, would be affected by the type and location of stored materials (spent nuclear fuel and high-level radioactive waste) in each region, the rate at which the contaminants were leached from the stored material, the amount of water (precipitation) available for dilution, and the thickness of the aquifer. For example, releases in Region 5 would probably be smaller and would occur later than those in other regions because of the region's lack of precipitation. This is indeed the case for commercial fuel, which is stored in above-grade concrete storage modules, stainless-steel dry storage canisters, and mostly intact corrosion-resistant zirconium alloy cladding.

However, early releases would occur in Region 5 because most DOE spent nuclear fuel is stored in below-grade vaults (see Appendix A, p. A-25) that would stop providing rain protection after 50 years (see Section K.2.1.1 for details). In addition, the analysis assumed no credit for the protectiveness of the DOE spent nuclear fuel cladding (see Section K.2.1.4.2 for details), which would result in releases that began early (about 800 years after weather protection was lost) and persist at a nearly constant rate for more that 6,000 years (DIRS 101937-Toblin 1998, p. 3).

The 10-meter (33-foot) doses listed in Table K-12 would be due to leachate concentrations from the storage area with no groundwater dilution. Downgradient doses decrease more rapidly in Regions 1 and 5 than in other regions because of greater groundwater dilution. The downgradient decrease in Region 5 would also be due to the relatively thick aquifer, which results in greater vertical plume spread and increases plume attenuation (DIRS 101937-Toblin 1998, pp. 4 to 6).

As shown in Table K-12, an onsite gardener in Region 5 could receive an internal committed dose as high as 3,300 rem for each year of ingestion of plutonium-239 and -240. However, the individual actually would receive only about 70 rem the first year, 140 rem the second year, 210 rem the third year, and so on until reaching an equilibrium annual dose (in approximately 50 years) of 3,300 rem per year. The individual would continue to receive this equilibrium dose as long as the radioactive material uptake remained constant.

If the annual doses are added, in less than 10 years the individual would have received more than 2,000 rem. If the International Commission on Radiological Protection risk conversion factor were applied to this dose, a probability of fatal cancer induction of 1 could be calculated. In other words, the use of this risk conversion would predict that 10 years of exposure would be virtually certain to produce a fatal cancer. This calculated risk is approximately 4 times greater than the lifetime risk of contracting a fatal cancer from all other causes (24 percent).

Table K-13 shows that the direct radiation dose rate to the onsite gardener could be as high as 7,300 rem per year. Unlike internal dose, this dose would actually be delivered during the year of exposure. This maximum value assumes a complete loss of shielding normally provided by the concrete storage module at the same time as the loss of weather protection (see Table K-1). Assuming a dose of 7,300 rem per year, the individual probably would die from acute radiation exposure. This dose would probably cause extensive cell damage in the individual that would result in severe acute adverse health conditions and death within weeks or months (DIRS 106184-NRC 1996, p. 8.29-5). However, these higher radiation dose rates are based on an early estimated time to structural failure of the concrete storage module. If these failure times were extended by as little as 100 years, the associated dose rates would decrease by a factor of 10 because the levels of radiation emanating from the degraded facilities would have decreased by about a factor of 10 due to radioactive decay (DIRS 150990-Rollins 1998, p. 12).

Table K-13. Estimated external peak dose rates (rem per year) for the onsite and near-site gardeners – Scenario 2.

		Maximally exposed individual distances (meters)[a] from storage facilities			
Region	Year of peak exposure[b]	10[c]	150	1,000	5,000
1	190	7,200	4	0.001	0.0
2	800	28	0.04	0.0	0.0
3	170	7,300	4	0.001	0.0
4	850	31	0.04	0.0	0.0
5	3,600	32	0.05	0.0	0.0

a. To convert meters to feet, multiply by 3.2808.
b. Years after 2116; Source: Adapted from DIRS 101910-Poe (1998, all).
c. Source: Adapted from (DIRS 101556-Davis 1998, all); the maximally exposed individual would be the onsite gardener.

The internal and external dose rates are presented separately because they would occur at different times and are therefore not additive.

K.3.2 UNUSUAL EVENTS

This section includes a quantitative assessment of potential accident impacts and a qualitative discussion of the impacts of sabotage.

K.3.2.1 Accident Scenarios

The analysis examined the impacts of accident scenarios that could occur during the above-ground storage of spent nuclear fuel and high-level radioactive waste and concluded that the most severe accident scenarios would be an aircraft crash into concrete storage modules or a severe seismic event. In Scenario 1, where storage would be in strong rigid concrete storage modules that had not degraded, the accident would not be expected to release radioactive material.

In Scenario 2, the concrete storage modules would deteriorate with time. If a severe natural event (for example, a hurricane) were to strike a degraded facility, a release of radioactive materials could occur earlier than predicted (see Section K.2) because of damage to the engineered barriers (concrete storage modules, dry storage canisters, material cladding, etc.). Section K.4 describes the potential effect of early loss of these barriers (see Table K-15 in Section K.4.3.1). However, DOE concluded that an aircraft crash into degraded concrete storage modules would dominate the consequences. The analysis evaluated the potential for criticality accidents and concluded that an event severe enough to produce meaningful consequences would be extremely unlikely, and that the consequences would be bounded by the aircraft crash consequences. Table K-14 lists the consequences of an aircraft crash on a degraded spent fuel concrete storage module.

Table K-14. Consequences of aircraft crash onto degraded spent nuclear fuel concrete storage module.[a]

Factor	High-population site[b]	Low-population site[c]
Frequency (per year)	3.2×10^{-6}	3.2×10^{-6}
Collective population dose (person-rem)	26,000	6,000
Latent cancer fatalities	13	3

a. Source: DIRS 103711-Davis, Strenge, and Mishima (1998, p. 11).
b. 330 persons per square mile.
c. 77 persons per square mile.

K.3.2.2 Sabotage

Storage of spent nuclear fuel and high-level radioactive waste over 10,000 years would entail a continued risk of intruder access at each of the 77 sites. Sabotage could result in a release of radionuclides to the environment around the facility. In addition, intruders could attempt to remove fissile material, which could result in releases of radioactive material to the environment. For Scenario 1, the analysis assumed that safeguards and security measures currently in place would remain in effect during the 10,000-year analysis period at the 77 sites. Therefore, the risk of sabotage would continue to be low. However, the difficulty of maintaining absolute control over 77 sites for 10,000 years would suggest that the cumulative risk of intruder attempts would increase.

For Scenario 2, the analysis assumed that safeguards and security measures would not be maintained at the 77 sites after approximately the first 100 years. For the remaining 9,900 years of the analysis period, the cumulative risk of intruder attempts would increase. Therefore, the risk of sabotage would increase substantially under this scenario.

K.4 Uncertainties

Section K.3 contains estimates of the radiological impacts of the No-Action Alternative, which assumes continued above-ground storage of spent nuclear fuel and high-level radioactive waste at sites across the United States. Associated with the impact estimates are uncertainties typical of predictions of the outcome of complex physical and biological phenomena and of the future state of society and societal institutions over long periods. DOE recognized this fact from the onset of the analysis; however, the predictions will be valuable in the decisionmaking process because they provide insight based on the best information and scientific judgments available.

This analysis considered five aspects of uncertainty:

- Uncertainties about the nature of changes in society and its institutions and values, in the physical environment, and of technology as technology progresses
- Uncertainties associated with future human activities and lifestyles
- Uncertainties associated with the mathematical representation of the physical processes and with the data in the computer models
- Uncertainties associated with the mathematical representation of the biological processes involving the uptake and metabolism of radionuclides and the data in the computer models
- Uncertainties associated with accident scenario analysis

The following sections discuss these uncertainties in the context of possible effects on the impact estimates reported in Chapter 7 and Section K.3.

K.4.1 SOCIETAL VALUES, NATURAL EVENTS, AND IMPROVEMENTS IN TECHNOLOGY

K.4.1.1 Societal Values

History is marked by periods of great social upheaval and anarchy followed by periods of relative political stability and peace. Throughout history, governments have ended abruptly, resulting in social instability, including some level of lawlessness and anarchy. The Scenario 1 assumption is that political stability would exist to the extent necessary to ensure adequate institutional control to monitor and maintain the spent nuclear fuel and high-level radioactive waste to protect the workers and the public for 10,000 years. The Scenario 2 assumption is that in the United States political stability would exist for 100 years into the future and that the spent nuclear fuel and high-level radioactive waste would be properly monitored and maintained and the public would be protected for this length of time. If a political upheaval were to occur in the United States, the government could have difficulty protecting and maintaining the storage facilities, and the degradation processes could begin earlier than postulated in Scenario 2. If institutional control were not maintained for at least 100 years, radioactive materials from the spent nuclear fuel and high-level radioactive waste could enter the environment earlier, which would result in higher estimated impacts due to the higher radiotoxicity of the materials. However, this scenario would probably increase overall impacts by no more than a factor of 2.

K.4.1.2 Changes in Natural Events

Because of the difficulty of predicting impacts of climate change (glaciation, precipitation, global warming), DOE decided to evaluate facility degradation and environmental transport mechanisms based on current climate conditions. For example, glaciation, which many scientists agree will occur again within 100,000 years, probably would cover the northeastern United States with a sheet of ice. The ice would crush all structures, including spent nuclear fuel and high-level radioactive waste storage facilities, and could either disperse the radioactive materials in the accessible environment or trap the materials in the ice sheet. In addition, large populations would migrate from the northeastern United States to warmer climates, thus changing the population distribution and densities throughout the United States (the coastline could move 100 miles out from its current position due to the reduced water in the oceans). Other scientists predict that global warming could lead to extensive flooding of low-lying coastal areas throughout the world. Such changes would have to be known with some degree of certainty to make accurate estimates of potential impacts associated with the release of spent nuclear fuel and high-level radioactive waste materials to the environment. To simplify the analysis, DOE has chosen not to attempt to quantify the impacts resulting from the almost certain climate changes that will occur during the analysis period.

K.4.1.3 Improvements in Technology

We are living in a time of unparalleled technical advancement. It is possible that cures for many common cancers will be found in the coming decades. In this regard, the National Council on Radiation Protection and Measurements (DIRS 101858-NCRP 1995, p. 51) states that:

> *One of the most important factors likely to affect the significance of radiation dose in the centuries and millennia to come is the effect of progress in medical technology. At some future time, it is possible that a greater proportion of somatic [cancer] diseases caused by radiation will be treated successfully. If, in fact, an increased proportion of the adverse health effects of radiation prove to be either preventable or curable by advances in medical science, the estimates of long-term detriments may need to be revised as the consequences (risks) of doses to future populations could be very different.*

Effective cures for cancer would affect the fundamental premise on which the No-Action Alternative impact analysis is based. However, this technology change was not included in the impact analyses.

Other advancements in technology could include advancements in water purification that could reduce the concentration of contaminants in drinking water supplies. Improved corrosion-resistant materials could reduce package degradation rates, which could reduce the release of contaminants and the resultant impacts. In addition, future technology could enable the detoxification of the spent nuclear fuel and high-level radioactive waste materials, thereby removing the risks associated with human exposure.

K.4.2 CHANGES IN HUMAN BEHAVIOR

General guidance for the prediction of the evolution of society has been provided by the National Research Council in *Technical Bases for Yucca Mountain Standards* (DIRS 100018-National Research Council 1995, pp. 28 and 70), in which the Committee on Technical Bases for Yucca Mountain Standards concluded that there is no scientific basis for predicting future human behavior. The study recommends policy decisions that specify the use of default (or reference) scenarios to incorporate future human behaviors into compliance assessment calculations. This No-Action Alternative analysis followed this approach, based on societal conditions as they exist today. In doing so, the analysis assumed that populations would remain at their present locations and that population densities would remain at the current levels. This assumption is appropriate when estimating impacts for comparison with other proposed actions; however, it does not reflect reality.

Although this analysis did not project the affected populations used in the No-Action Alternative to 2035, as DOE has done in other parts of the EIS, the potential effect on the outcome would be an increase in collective impacts of less than a factor of 1.5, which is the average expected increase in national population from 1990 to 2035 (DIRS 152471-Bureau of the Census 2000, all). In addition to changing in size, populations are constantly moving. If, for example, populations were to move closer to and increase in size in areas near the storage facilities, the radiation dose and resultant adverse impacts could increase substantially. However, DOE has no way to predict such changes accurately and, therefore, did not attempt to quantify the resultant effects on overall impacts.

Another lifestyle change that could affect the overall impacts would involve food consumption patterns. For example, people might curtail their use of public water supplies derived from rivers if they learned that the river water carried carcinogens. Widespread adoption of such practices could reduce the impacts associated with the drinking water pathway.

K.4.3 MATHEMATICAL REPRESENTATIONS OF PHYSICAL PROCESSES AND OF THE DATA INPUT

The DOE approach for the No-Action Alternative was to be as comparable as possible to the approach used for the predictions of impacts from the proposed Yucca Mountain Repository to enable direct comparisons of the impact estimates for the two cases. Therefore, the analysis either used the process models developed for the TSPA-VA directly or adapted them for the No-Action Alternative impact calculations. For processes that were different from those treated in the TSPA-VA, DOE developed analytical approaches.

In a general sense, the TSPA-VA calculations used a stochastic (random) approach to develop radiological impact estimates. Existing process models were used to generate a set of responses for a particular process. In the TSPA-VA process, the impact calculations sample each set of process responses and calculate a particular impact result. A large number of calculations were performed. From the set of variable results, an expected value can be identified, as can a distribution of results that is an indication of the uncertainties in the calculated expected values.

For the No-Action Alternative analysis, the calculations were based on only a single set of best estimate parameters. No statistical distribution of results was generated as a basis for the quantification of uncertainties. This section describes the uncertainties associated with the input data and modeling used to evaluate the rates of degradation of the materials considered in this document and to estimate the impacts of the resulting releases. It describes the key assumptions, shows where the assumptions are consistent with TSPA-VA assumptions, and qualitatively assesses the magnitude of the uncertainties caused by the assumptions.

Calculating the radiological impacts to human receptors required a mathematical representation of physical processes (for example, water movement) and data input (for example, material porosity). There are uncertainties in both the mathematical representations and in the values of data. The TSPA-VA accommodates these uncertainties by using a probabilistic approach to incorporate the uncertainties, whereas the No-Action analysis uses a deterministic approach in combination with an uncertainty analysis. When done correctly, both approaches yield the same information, although, as in the case of the TSPA-VA, the probabilistic approach provides quantitative information.

K.4.3.1 Waste Package and Material Degradation

The major approaches and assumptions used for the No-Action Scenario 2 analysis are listed in Table K-15. The table indicates where the continued storage calculations followed the basic methods developed for the TSPA-VA. It also indicates the processes for which models other than those used in the TSPA-VA were applied.

DOE analyzed surface storage of commercial spent nuclear fuel in horizontal stainless-steel canisters inside concrete storage modules. There are other probable forms of storage, including horizontal and

Table K-15. Review of approaches, assumptions, and related uncertainties[a] (page 1 of 2).

Approach or assumption	Consistent with repository analysis assumptions	Sensitivity of impacts to approach or assumption[b]
Period of analysis – 10,000 years	Yes	None
Commercial spent nuclear fuel, DOE spent nuclear fuel, and high-level radioactive waste quantities equivalent to NWPA specified 70,000 MTHM and Module 1	Yes	None
No credit for stainless-steel cladding on commercial spent nuclear fuel	Yes	If credit were taken for stainless-steel cladding, LCFs[a] could decrease by as much as a factor of 10.
0.1 percent of zirconium alloy cladding is initially failed	Yes	If initial zirconium-alloy-clad fuel cladding failure had been assumed to be as low as zero or as high as 100 percent impacts could have been slightly smaller (additional protection from winds) to a factor of 20 higher, respectively.
Concrete storage module weather protection	This is a primary protective barrier for the No-Action analysis and is not applicable to TSPA	If weather protection from the concrete storage module had not been assumed in the No-Action analysis, LCFs could be higher by less than a factor of 10.
Concrete base pad degradation	Not applicable	Used NRC recommended values (probably overestimated degradation and reduced consequences in the No-Action analysis); increase in LCFs by probably more than a factor of 2 but less than a factor of 10
Credit for stainless-steel canister on high-level radioactive waste	No; TSPA does not take credit for stainless-steel container	If the No-Action analysis had not taken credit for the stainless-steel canister, LCFs would change very little (slight increase) because of the intrinsic stability of the borosilicate glass.
DOE spent nuclear fuel evaluated by a representative surrogate that is based mostly on DOE N-Reactor spent nuclear fuel (other spent nuclear fuel types not evaluated)	Yes	If actual fuel types were evaluated, LCFs could either increase or decrease by less than a factor of 2.
No credit given for zirconium alloy cladding on N-Reactor spent nuclear fuel	Yes	If credit was given for the N-Reactor zirconium alloy cladding, the LCFs would decrease by less than a factor of 2.
Stainless steel deterioration	Model paralleled TSPA approach for Alloy-22	Model based on best information; if incorrect and corrosion proceeds more rapidly and stainless steel offers no protection, LCFs would increase by less than 25 percent.
Zirconium alloy cladding deterioration	Yes, very slow corrosion rate.	If the No-Action analysis had assumed larger or smaller deterioration rates, LCFs could have increased by several orders of magnitude or decreased by less than a factor of 2.
Zirconium alloy cladding credit	Yes	If the No-Action analysis had not taken credit for zirconium alloy cladding, LCFs could have increased by as much as 2 orders of magnitude.
Deterioration of spent nuclear fuel and high-level radioactive waste core materials	Yes	None

Table K-15. Review of approaches, assumptions, and related uncertainties[a] (page 2 of 2).

Approach or assumption	Consistent with repository analysis assumptions	Sensitivity of impacts to approach or assumption[b]
Use of recent regional climate conditions to determine deterioration (temperature, precipitation, etc.)	No; No-Action analysis used constant "effective" regional weather parameters weighted for material inventories and potentially affected downstream populations; TSPA used actual weather patterns measured at Yucca Mountain. The TSPA also assumed long-term climate changes would occur in the form of increased precipitation.	If actual site climate data and projected future potential climate changes had been considered in the No-Action analysis, LCFs could have increased or decreased by as much as a factor of 10. Climate change assumptions such as a glacier covering most of the northeastern seaboard of the United States would have made estimating impacts from continued storage virtually impossible.
Surface transport by precipitation	Not applicable; TSPA only considered groundwater transport because there is no surface-water transport pathway possible for the repository.	If the No-Action analysis had not considered the groundwater transport pathway, LCFs could have been as much as a factor of 10 higher.
Regional binning of sites – not specific site parameters	Not applicable; TSPA considered only a single site; the No-Action analysis evaluated potential impacts from 77 sites on a regional basis.	The No-Action analysis binned sites into categories and developed "effective" regional climate conditions such that calculated impacts would be comparable to those which could be calculated by a site-specific analysis.
Atmospheric dose consequences judged to be small when compared to liquid pathways.	Yes	Small impact on LCFs.
Drinking water doses	Yes; primary pathway evaluated	Use of drinking-water-only pathway underestimates total collective LCFs by less than a factor of 3.
Used the Multimedia Environmental Pollutant Assessment System[c] modeling approach for calculating population uptake/ingestion	No; TSPA uses GENII-S.[d] GENII-S uses local survey data; the Multimedia Environmental Pollutant Assessment System uses EPA/NRC exposure/uptake default and actual population data	No impact. The two programs yield comparable results as used in these analyses.
ICRP[e] approach to calculate dose commitment from ingested radionuclides	Yes	No impact.
Human health impacts calculated as LCFs with NCRP[f] conversion factors	NA; TSPA does not estimate LCFs.	Use of other than the linear no-threshold model could result in a change in estimated LCFs from 0.25 to 2 times the nominal value.[g]

a. Abbreviations: NWPA = Nuclear Waste Policy Act; MTHM = metric tons of heavy metal; LCF = latent cancer fatality; TSPA = Total System Performance Assessment; NRC = Nuclear Regulatory Commission; ICRP = International Commission on Radiological Protection; EPA = Environmental Protection Agency.
b. Sensitivity of impacts to approach/assumption is based on professional judgement and, if applicable, the effects of the approaches/assumptions on calculations.
c. DIRS 101533-Buck et al. (1995, all).
d. DIRS 100464-Leigh et al. (1993, all).
e. DIRS 110386-ICRP (1979, all).
f. DIRS 101857-NCRP (1993, p. 112).
g. DIRS 101884-NCRP (1997, p. 75).

vertical casks made of materials ranging from stainless steel to carbon steel. Degradation and releases from vertical carbon-steel casks were evaluated qualitatively. Such storage units would be likely to fail from corrosion earlier than concrete and stainless steel. The concrete and stainless-steel units were calculated to fail and begin releasing their contents at about 1,000 years after the assumed loss of institutional control. The less-resistant carbon-steel units could begin releasing their contents earlier and their use would result in a longer period of release and increased impacts. This difference is likely to be an increase of 10 to 30 percent in population dose commitment and resultant latent cancer fatalities.

K.4.3.2 Human Health Effects

The dose-to-risk conversion factors typically used to estimate adverse human health impacts resulting from radiation exposures contain considerable uncertainty. The risk conversion factor of 0.0005 latent cancer fatality per person-rem of collective dose for the general public typically used in DOE National Environmental Policy Act documents is based on recommendations of the International Commission on Radiological Protection (DIRS 101836-ICRP 1991, p. 22) and the National Council on Radiation Protection and Measurements (DIRS 101857-NCRP 1993, p. 112). The factor is based on health effects observed in the high dose and high dose rate region (20 to 50 rem per year). Health effects were extrapolated to the low-dose region (less than 10 rem per year) using the linear no-threshold model. This model is generally recommended by the International Commission on Radiological Protection and the National Council of Radiation Protection and Measurements, and most radiation protection professionals believe this model produces a conservative estimate (that is, an overestimate) of health effects in the low-dose region, which is the exposure region associated with continued storage of spent nuclear fuel and high-level radioactive waste. This report summarizes estimates of the impacts associated with very small chronic population doses to enable comparison of alternatives in this EIS.

According to the National Council on Radiation Protection and Measurements, the results of an analysis of the uncertainties in the risk coefficients "show a range (90 percent confidence intervals) of uncertainty values for the lifetime risk for both a population of all ages and an adult worker population from about a factor of 2.5 to 3 below and above the 50th percentile value" (DIRS 101884-NCRP 1997, p. 74).

The National Council on Radiation Protection and Measurements states, "This work indicates that given the sources of uncertainties considered here, together with an allowance for unspecified uncertainties, the values of the lifetime risk can range from about one-fourth or so to about twice the nominal values" (DIRS 101884-NCRP 1997, p. 75).

Because of the large uncertainties that exist in the dose/effect relationship, the Health Physics Society has recommended "…against quantitative estimation of health risks due to radiation exposure below a lifetime dose of 10 rem …" (DIRS 101835-Mossman et al. 1996, p. 1). In essence, the Society has recommended against the quantification of risks due to individual radiation exposures comparable to those estimated in the No-Action analysis. These uncertainties are due, in part, to the fact that epidemiological studies have been unable to demonstrate that adverse health effects have occurred in individuals exposed to small doses (less than 10 rem per year) over a period of many years (chronic exposures) and to the fact that the extent to which cellular repair mechanisms reduce the likelihood of cancers is unknown.

Other areas of uncertainty in estimation of dose and risk include the following:

- *Uncertainties Related to Plant and Human Uptake of Radionuclides.* There are large uncertainties related to the uptake (absorption) of radionuclides by agricultural plants, particularly in the case where "regionalized," versus "site-specific" data are used. Also of importance are variations in the absorption of specific radionuclides through the human gastrointestinal tract. Factors that influence the absorption of radionuclides include their chemical or physical form, their concentrations, and the presence of stable elements having similar chemical properties. In the case of agricultural crops, many of these factors are site-specific.

- *Uncertainties in Dose and Risk Conversion Factors.* The magnitudes and sources of the uncertainties in the various input parameters for the analytical models need to be recognized. In addition to the factors cited above, these include those required for converting absorbed doses into equivalent doses, for calculating committed doses, and for converting organ doses into effective (whole body) doses. Although these various factors are commonly assigned point values for purposes of dose and risk estimates, each of these factors has associated uncertainties.

- *Conservatisms in Various Models and Parameters.* In addition to recognizing uncertainties, one must take into account the magnitudes and sources of the conservatisms in the parameters and models being used. These include the fact that the values of the tissue weighting factors and the methods for calculating committed and collective doses are based on the assumption of a linear no-threshold relationship between dose and effect. As the International Commission on Radiological Protection and the National Council on Radiation Protection and Measurements have stated, the use of the linear no-threshold hypothesis provides an upper bound on the associated risk (DIRS 147927-ICRP 1966, p. 56). Also to be considered is that the concept of committed dose could overestimate the actual dose by a factor of 2 or more (DIRS 101856-NCRP 1993, p. 25).

K.4.3.3 Accidents and Their Uncertainty

The accident methodology used in this analysis is described in Section K.2.5 for Scenarios 1 and 2. It states that for Scenario 1 an aircraft crash into the storage array would provide the most severe accident scenario and its consequences would not cause a release from the rugged concrete storage module. The analysis placed considerable weight on the quality and strength of the concrete storage module and dry storage canister. For an analysis extending 10,000 years, more severe natural events can be postulated than those used as the design basis for the dry storage canister, and they could cause failure of the canister. This could exceed the consequences estimated for Scenario 1, but it would be unlikely to exceed the consequences for the aircraft accident scenario evaluated for Scenario 2.

Section K.2.5.1 concludes that the aircraft crash on the degraded concrete storage modules would be the largest credible event that could occur. The best estimate impacts from this event ranged from 3 latent cancer fatalities for a low-population site to 13 for a high-population site. The uncertainties in these estimates are very large. As discussed above, the aircraft crash could cause a minimum of no latent cancer fatalities given the uncertainty in the model that converts doses to cancers. The maximum impact could be substantially greater than the estimated values if an aircraft crash involving the largest commercial jet occurred at the time of initial concrete storage module degradation at a specific site under adverse weather conditions (conditions that would maximize the offsite doses) involving spent fuel with the maximum expected inventory of radionuclides.

K.4.4 UNCERTAINTY SUMMARY

The sections above discuss qualitatively and semiquantitatively the uncertainties associated with impact estimates resulting from the long-term storage of spent nuclear fuel and high-level radioactive waste at multiple sites across the United States. As stated above, DOE has not attempted to quantify the variability of estimated impacts related to possible changes in climate, societal values, technology, or future lifestyles. Although uncertainties with these changes could undoubtedly affect the total consequences reported in Section K.3 by several orders of magnitude, DOE did not attempt to quantify these uncertainties to simplify the analysis.

DOE attempted to quantify a range of uncertainties associated with mathematical models and input data, and estimated the potential effect these uncertainties could have on collective human health impacts. By summing the uncertainties discussed in Sections K.4.1, K.4.2, and K.4.3 where appropriate, DOE estimates that total collective impacts over 10,000 years could have been underestimated by as much as 3 or 4 orders of magnitude. However, because there are large uncertainties in the models used for quantifying the relationship between low doses (that is, less than 10 rem) and the accompanying health impacts, especially under conditions in which the majority of the populations would be exposed at a very low dose rate, the actual collective impact could be small.

On the other hand, impacts to individuals (human intruders) who could move to the storage sites and live close to the degraded facilities could be severe. During the early period (200 to 400 years after the assumed loss of institutional control), acute exposures to external radiation from the spent nuclear fuel and high-level radioactive waste material could result in prompt fatalities. In addition, after a few thousand years onsite shallow aquifers could be contaminated to such a degree that consumption of water from these aquifers could result in severe adverse health effects, including premature death. Uncertainties related to these localized impacts are related primarily to the inability to predict accurately how many individuals could be affected at each of the 77 sites over the 10,000-year analysis period. In addition, the uncertainties associated with localized impacts would exist for potential consequences resulting from disruptive events, both manmade and natural.

Therefore, as listed in Table K-15, uncertainties resulting from future changes in natural phenomena and human behavior that cannot be predicted, process model uncertainties, and dose-effect relationships, taken together, could produce the results presented in Section K.3, overestimating or underestimating the impacts by as much as several orders of magnitude. Uncertainties of this magnitude are typical of predictions of the outcome of complex physical and biological phenomena over long periods. However, these predictions (with their uncertainties) are valuable to the decisionmaking process because they provide insight based on the best information available.

REFERENCES

Note: In an effort to ensure consistency among Yucca Mountain Project documents, DOE has altered the format of the references and some of the citations in the text in this Final EIS from those in the Draft EIS. The following list contains notes where applicable for references cited differently in the Draft EIS.

104597 Battelle 1998 — Battelle Pacific Northwest Division 1998. *Analytical Approach for Estimating Releases of Spent Nuclear Fuel and High-Level Waste for the Yucca Mountain Environmental Impact Statement No-Action Alternative*. Las Vegas, Nevada: Jason Technologies. ACC: MOL.19990513.0039.

101533 Buck et al. 1995 — Buck, J.W.; Whelan, G.; Droppo, J.G., Jr.; Strenge, D.L.; Castleton, K.J.; McDonald, J.P.; Sato, C.; and Streile, G.P. 1995. *Multimedia Environmental Pollutant Assessment System (MEPAS) Application Guidance, Guidelines for Evaluating MEPAS Input Parameters for Version 3.1*. PNL-10395. Richland, Washington: Pacific Northwest Laboratory. TIC: 242139.

152471 Bureau of the Census 2000 — Bureau of the Census 2000. "National Population Projections I. Summary Files." Washington, D.C.: Bureau of the Census. Accessed August 28, 2000. ACC: MOL.20010725.0152. http://www.census. gov/population/www/projections/natsum-T1.html